INFLUENCE OF DIRECT URCA PROCESSES IN A STRONG MAGNETIC FIELD ON DYNAMICS OF COLLAPSING STAR ENVELOPE

A.A. Gvozdev, I.S. Ognev

Department of Theoretical Physics, Yaroslavl State University, Sovietskaya 14, Yaroslavl 150000, Russia.
E-mail: *gvozdev@uniyar.ac.ru, ognev@uniyar.ac.ru*

ABSTRACT. Direct URCA processes in a collapsing star envelope with a strong magnetic field are investigated. It is shown that in the toroidal magnetic field these processes can develope a torque which quickly unwinds an envelope. A general expression for a force density along the field direction is obtained. An influence of the neutrino unwinding effect on a dynamics of the collapsar envelope is discussed and numerically estimated.

Key words: URCA processes: magnetic field: collapsing star remnant: envelope.

1. Introduction

Collapsing star systems with millisecond remnants are of great interest in astrophysics now. Such remnants can be produced, for example, in a type II Supernova explosion [1, 2], in a coalescense of a closed binary system of neutron stars [3] and in an accretion induced collapse [4]. In the model of a spherically symmetric collapse, such a systems have common properties during few seconds after a protostar contraction. At this time a collapsing star remnant is formed. It is usually assumed that the remnant consists of a compact rigid- rotating core and a differently rotating envelope.

The compact core with the typical size $R_o \sim 10 km$, the supranuclear density $\rho \gtrsim 10^{13} g/cm^3$, and the high temperature $T \gtrsim 10 MeV$ is opaque to neutrinos. A remnant envelope with the typical size of few tens of kilometers, the density $\rho \sim 10^{11} - 10^{12} g/cm^3$ and the temperature $T \sim 3 - 6 MeV$ is partially transparent to the neutrino flux. Anomalously high neutrino flux with the typical luminosity $L_\nu \sim 10^{52} erg/s$ is emitted from the remnant during 2 - 3 seconds after the collapse. As the result of a high rotating frequency and a medium viscosity of a remnant a turbulent dynamo and a large gradient of angular velocities are inevitably produced during a star contraction. The extremely strong poloidal magnetic field up to $B \sim 10^{15} G$ could be generated by a dynamo process in a remnant [5]. On the other hand, a large gradient of angular velocities in the vicinity of a rigid rotating millisecond core can generate more strong toroidal magnetic field (TMF) with the strength $B \sim 10^{15} - 10^{17} G$ during a second [6]. Note, that TMF can affect significantly the dynamics of the remnant envelope even if this field exists

during few seconds. For example, TMF with $B \sim 10^{17}G$ can initiate the process of a mantle shedding [1] and be an engine of an anisotropic γ-ray burst [2] in a Supernova II explosion.

2. Momentum asymmetry in direct URCA processes

It is important to investigate the influence of the neutrino propagation through a magnetized medium on dynamics of the remnant envelope. Indeed, neutrinos are emitted and absorbed asymmetrically with respect to the magnetic field direction [7] as the result of the parity violation in weak processes. N.Chugai was the first who considered the neutrino recoil momentum as a possible source of an anomalously large pulsar kick velocity [8].

In the present paper we discuss an asymmetry of a momentum transferred by neutrinos to the medium along the magnetic field direction in direct URCA processes:

$$p + e^- \Longleftrightarrow n + \nu_e, \tag{1}$$

$$n + e^+ \Longleftrightarrow p + \tilde{\nu}_e \tag{2}$$

The asymmetry can lead to a macroscopic torque spins up the envelope with TMF.

A quantitative estimation of the effect can be obtained from the four-vector of the energy-momentum transferred by neutrinos to a unit volume of the envelope per unit time:

$$\frac{dP_\alpha}{dt} = \left(\frac{dQ}{dt}, \vec{\Im} \right) = \frac{1}{V} \int \prod_i dn_i f_i \prod_f dn_f (1 - f_f) \frac{|S_{if}|^2}{\mathcal{T}} k_\alpha, \tag{3}$$

where dn_i and dn_f are the initial and final state numbers in the phase space element,f_i and f_f are the distribution functions of initial and final particles, k_α is the neutrino four- momentum transferred in a single reaction, $|S_{if}|^2/\mathcal{T}$ is a process S-matrix element squared per unit time.

To calculate the components of the energy-momentum vector we note that, in accordance with envelope conditions, the nucleonic gas is Boltzmann and nonrelativistic one. We also assume that medium parameters and the magnetic field strength satisfy following unequalities:

$$m_p T \gg eB \gtrsim \mu_e^2, T^2 \gg m_e^2. \tag{4}$$

It means that ultrarelativistic electrons and positrons occupy the ground Landay level only while the protons occupy quite many levels. We employ the neutrino distribution function in absence of the magnetic field. This is a good approximation when the region occupies by the strong magnetic field is smaller or of the order of the neutrino mean-free path. In the TMF generation model the region occupies by such a field is not larger then several kilometers [6], while the estimation of the neutrino mean- free path due to direct URCA processes gives:

$$l_\nu \simeq 4km \left(\frac{4.4 \times 10^{16}G}{B} \right) \left(\frac{5 \times 10^{11}g/cm^3}{\rho} \right) .$$

So, the magnetic field cannot strongly influence the neutrino distribution and we can use the one-dimensional factorized neutrino distribution function:

$$f_\nu = \frac{\Phi_\nu(r, \chi)}{\exp\left(\omega/T_\nu - \eta_\nu \right) + 1}, \tag{5}$$

where T_ν is the neutrino spectral temperature, η_ν is a fitting parameter, χ is the cosine of the angle between the radial direction and the neutrino momentum.

Under all these assumptions we obtain the following general expression for the force density along the magnetic field direction in URCA processes:

$$\Im_{\parallel}^{(urca)} = \mathcal{N}\left(3\langle\chi^2\rangle - 1\right)\frac{N_n}{N_B}\left[\exp\left(\delta\eta - a\right)I(a) + I(-a)\right] -$$
$$- \frac{1}{2}\frac{g_a^2 - 1}{3g_a^2 + 1}\left(1 - \langle\chi^2\rangle\right)\frac{dQ^{(urca)}}{dt} , \tag{6}$$

$$I(a) = \int\limits_0^\infty \frac{y^3 dy}{e^{y-a} + 1}, \quad a = \frac{\mu_e - (m_n - m_p)}{T},$$

$$\delta\eta = (\mu_e + \mu_p - \mu_n)/T, \quad N_B = N_n + N_p,$$

$$\langle\chi^2\rangle = \langle\chi_{\tilde\nu}^2\rangle \simeq \langle\chi_\nu^2\rangle = \left(\int \chi^2\,\omega\,f_\nu\,d^3k\right)\left(\int \omega\,f_\nu\,d^3k\right)^{-1},$$

where μ_e, μ_p and μ_n are chemical potentials of electrons, protons and neutrons, N_n and N_p are the number densities of neutrons and protons. The dimensional factor $\mathcal{N}$ is defined as:

$$\mathcal{N} = \frac{G_F^2\cos^2\theta_c}{(2\pi)^3}\frac{g_a^2 - 1}{3}eB\,T^4\,N_B, \tag{7}$$

where $g_a \simeq 1.26$ is the axial constant of the nucleonic current, G_F is the Fermi constant, θ_c is the Cabbibo angle. As it is seen from Eq. (6), the neutrino momentum asymmetry transferred to the shell along the magnetic field is produced by two sources: the first one is an anisotropy of the neutrino distribution ($\langle\chi^2\rangle \neq 1/3$) and the second one is the energy transfer to the shell by URCA processes ($dQ^{(urca)}/dt \neq 0$). Hence, the momentum asymmetry takes place in the case of non-equilibrium neutrino distribution function only [9]. As for the envelope medium, it is considered to be in the local quasi-equilibrium which is defined by the following conditions:

$$\Gamma_{n\to p} = \Gamma_{p\to n}, \quad dQ^{(urca)}/dt = 0,$$

where Γ is the reaction rate. We assume the medium density and the field strength to be preset values. Using the additional conditions: $d\rho/dt = 0$ and $N_p = N_{e^-} - N_{e^+}$, we can obtain all medium parameters from the conditions of the local quasi-equilibrium.

3. Numerical estimations

For numerical estimations we use neutrino parameters: $T_{\nu_e} \simeq 4MeV$, $T_{\tilde\nu_e} \simeq 5MeV$ and $\eta_\nu \simeq \eta_{\tilde\nu} \simeq 0$ from Ref. 10, where the Boltzmann equation in the model of a spherically symmetric collapse on the basic neutrino emission stage was solved numerically. For the envelope region with the typical density $\rho = 5 \times 10^{11}g/cm^3$ the numerical value of the mean cosine squared is $\langle\chi_\nu^2\rangle \simeq 0.4$. Provided that the magnetic field strength is $B = 4 \times 10^{16}G$, we obtain from the conditions of the local quasi-equilibrium:

$$T \simeq T_{\nu_e}, \quad a \simeq 3, \quad N_p/N_B \simeq 0.07.$$

Using these parameters, we estimate the force density along the magnetic field direction (6), as:

$$\Im_{\parallel}^{(urca)} \simeq 1.8 \times 10^{20} dynes/cm^3\left(\frac{T}{4\,MeV}\right)^4\left(\frac{B}{4.4 \times 10^{16}G}\right)\left(\frac{\rho}{5 \times 10^{11}g/cm^3}\right) .$$

As one can see, the force density directs along the magnetic field $\vec{B}$. Surprisingly, another important process of neutrino-nucleon scattering gives the contribution to the force density of the same sign and approximately twice larger than the direct URCA [11]. Hence, the estimation for the total force density in the dominant processes (the direct URCA and the neutrino-nucleon scattering) is:

$$\Im_{\parallel}^{(urca)} \simeq 5 \times 10^{20} dynes/cm^3 \left(\frac{B}{4.4 \times 10^{16}G} \right) \left(\frac{\rho}{5 \times 10^{11} g/cm^3} \right) \; .$$

The angular acceleration produced by the torque exerts by such a force is:

$$\dot{\Omega} \sim 10^3 s^{-2} \left(\frac{B}{4.4 \times 10^{16}G} \right) \left(\frac{R_o}{10km} \right).$$

Note that this acceleration is large enough to spin up the region of the remnant envelope containing the strong TMF to the typical velocities of millisecond pulsars in a time of order a second.

4. Conclusion

We consider collapsing star systems with millisecond remnants containing a strong TMF on the stage of a basic neutrino emission and estimate the force density along the magnetic field direction in direct URCA processes. The angular acceleration produced by the force is large enough to affect significantly on the remnant magneto-hydro-dynamics (MHD). Hence, the neutrino "spin-up" effect should be taken into account in analysis of the full system of MHD equations. In particular, this effect can influence on the mechanism of the TMF generation, the mantle-shedding process, the mechanism leading to the formation of anisotropic GRB and also can provoke a formation of some MHD instabilities.

References

[1] Bisnovatyi-Kogan G.S.: 1970, *Astron. Zh. Akad. Nauk. SSSR,* **47**, 813;
Bisnovatyi-Kogan G.S.: 1989, *Physical Problems of the Theory of Stellar Evolution* [in Russian], Nauka, Moscow.

[2] Woosley S.E.: 1993, *Astrophys. J.,* **405**, 473;
MacFadyen A., Woosley S.E.: 1998, Preprint astro-ph/9810274.

[3] Ruffert M., Janka H.-T.: 1998, *Astron. and Astrophys.,* **338**, 535.

[4] Spruit H.C.: 1998, Preprint astro-ph/9811007.

[5] Duncan R.C., Thompson C.: 1992, *Astrophys. J.,* **9**, L392.

[6] Bisnovatyi-Kogan G.S., Moiseenko S.G.: 1993, *Astron. Astrophys. Trans.,* **3**, 287.

[7] Dorofeev O.F. et al.: 1984, *JETP Lett.,* **40**, 159.

[8] Chugai N.N.: 1984, *Pis'ma Astron. Zh.,* **10**, 210.

[9] Kusenko A., Segre G., Vilenkin A.: 1998, *Phys. Lett.,* **B437**, 359.

[10] Yamada S., Janka H.-T., Suzuki H.: 1998, Preprint astro-ph/9809009.

[11] Ognev I.S., Gvozdev A.A., these Proceedings.